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# On art, science, and the conservation of subterranean ecosystems

Stefano Mammola[1,2,3], Jagoba Malumbres-Olarte[2,4], Ilaria Vaccarelli[1,5,6], Veronica Nanni[1,6], Adrià Bellvert[1], Ivan Jarić[7,8]

**1** *Molecular Ecology Group, Water Research Institute, National Research Council, Verbania, Italy* **2** *Finnish Museum of Natural History, University of Helsinki, Helsinki, Finland* **3** *NBFC, National Biodiversity Future Center, Palermo, Italy* **4** *CE3C – Centre for Ecology, Evolution and Environmental Sciences, LIBRe – Laboratory for Integrative Biodiversity Research, CHANGE – Institute for Global Change and Sustainability, University of the Azores, Terceira, and University of Lisbon, 1749-016 Lisboa, Portuga* **5** *Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy* **6** *School for Advanced Studies IUSS, Science, Technology and Society Department, Pavia, Italy* **7** *Université Paris-Saclay, CNRS, AgroParisTech, Ecologie Systématique Evolution, Gif-sur-Yvette, France* **8** *Biology Centre of the Czech Academy of Sciences, Institute of Hydrobiology, České Budějovice, Czech Republic*

**Corresponding author:** Stefano Mammola (stefano.mammola@cnr.it)

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## Abstract

Caves, with their unique geologic and biological features, have inspired human imagination throughout history. From photography to movies, through comics, painting, and poetry, subterranean ecosystems feature prominently in various forms of artistic expression, often incorporating scientific ideas or concepts. Integrating art with science offers a powerful way to convey the uniqueness and importance of the organisms that inhabit subterranean ecosystems, emphasizing their importance as providers of key ecological and cultural services. This, in turn, would help promote their conservation. We discuss realized and unrealized connections between subterranean biologists and artists, aiming to achieve broader protection for subterranean ecosystems. We showcase the different art forms that depict subterranean environments, explain how each aligns with conservation science, and highlight the mutual benefits artists and researchers in subterranean biology can derive from collaboration. In doing so, we pose two important questions: How can we effectively bridge the cultural divide between subterranean scientists and artists? And how can we assess the effectiveness of art in enhancing science communication about subterranean ecosystems and their conservation? By addressing these questions, we envision a future where art and science intersect to safeguard the rich and diverse subterranean biological and cultural heritage.

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**Keywords**
Artistic expression, conservation art, conservation science, environmental communication, interdisciplinarity, public engagement, scientific visualization, science communication

## Art goes underground

"*In 15,000 years, we have invented nothing!*" Pablo Picasso is said to have exclaimed, shaking his head, upon seeing the Paleolithic art in Altamira cave, Spain – an anecdote widely regarded as apocryphal. However, it serves as a reminder that humans have been using cave walls as canvases for a very long time (Fig. 1a). Since then, caves have evolved from serving as artistic media to becoming central subjects in modern and contemporary art. From abstract paintings (Fig. 1b) to graffiti (Fig. 1c), through figurative art (Fig. 1d, e), comics (Fig. 1f), and music (Fig. 1g), caves and their biota have been prominently featured in various forms of artistic expression, which often incorporate scientific ideas or concepts. For instance, Sebastião Salgado's "Genesis" photographic series includes haunting images of cave formations that emphasize the untouched beauty of subterranean landscapes. Werner Herzog's documentary "Cave of Forgotten Dreams" explores the Chauvet Cave's prehistoric art, offering a meditative look at the intersection of time, art, and human consciousness. In painting, the work of contemporary artist Anselm Kiefer frequently features cave-like structures, exploring themes of memory, history, and mythology; whereas in poetry, Seamus Heaney's poem "The Underground" uses the imagery of caves and tunnels to explore themes of fear, wonder, and the unknown.

Caves and other subterranean ecosystems have increasingly become the protagonists of entire exhibitions, such as "Subterranean" at Amos Rex in Helsinki (2 April – 21 August 2022) and more recently, "Subterranean worlds" (*Mondes souterrains*) at Louvre Lens Museum in Paris (27 March – 22 July 2024) (Fig. 1h). While these expositions celebrated the beauty and mysteries of hidden subterranean worlds, they also underscored the growing pressures human activities pose on these ecosystems, drawing attention to the critical need for their conservation (Mammola et al. 2019). For example, the pamphlet of Amos Rex's "Subterranean" exhibition emphasizes how "*Humanity has carved its own footprint beneath the surface of the earth [...]. These themes are central to the works of many contemporary artists who comment on political conflicts and globally unsustainable development*". Given this example and others, we contend that the convergence of art and science for promoting the conservation of subterranean environments holds great promise. The question remains: how can artists and scientists collaborate most effectively to safeguard the rich heritage hidden beneath our feet?

## The importance of art for subterranean science and conservation

The idea of bridging science and art to foster environmental education and improve communication is not new (e.g., Jacobson et al. 2007; Opermanis et al. 2015; Dixon et al. 2015). The intersection of art and science enriches both fields, making scien-

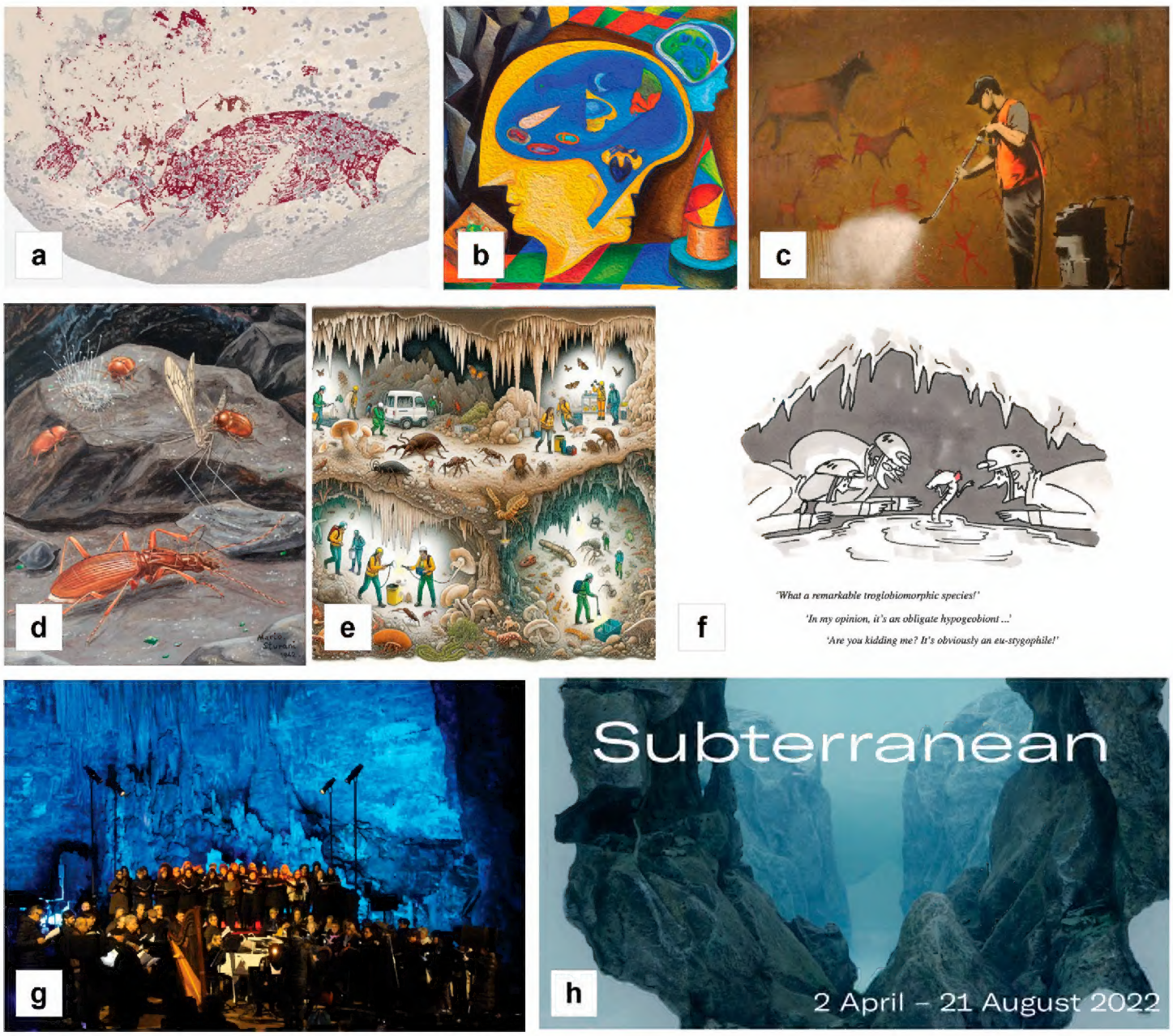



**Figure 1.** The breadth and scope of subterranean-related art. **a** Oldest known drawings on a cave wall in Indonesia, dating back 51,200 years (modified from Oktaviana et al. 2024) **b** "Pop Art Cubism Mind in Cave" (2022) by David S. Soriano (CC BY-SA 4.0) **c** street art by Banksy "Cave Painting Removal" (2008). Photo by Badjonni (CC BY-NC-SA 2.0) **d** the fauna of the Borna Maggiore di Pugnetto cave, Italy, as depicted in a distemper painting by Mario Sturani (1906–1978). Courtesy of the Sturani family, published in Sturani (1942) **e** an example of figurative art created using artificial intelligence (DALL-E) with the prompt "*Create an image about the impact of human activities on cave biota.*" Such AI tools are increasingly being used by scientists, particularly for science communication (Box 1) **f** cartoon by Irene Frigo illustrating the often-self-inflicted challenge faced by subterranean scientists in deciding how to best refer to cave-dwelling animals. Courtesy of Irene Frigo, published in Martínez and Mammola (2021) **g** a concert in the Castellana Cave, Italy. Photo by Mafalda Baccaro (CC BY-NC-ND 2.0) **h** "Subterranean" (Amos Rex, Helsinki, 2 April – 21 August 2022), was an exhibition dedicated to the underground world. It included a section highlighting the impacts of human activities on subterranean ecosystems.

tific knowledge more approachable and engaging, while also helping to promote pro-conservation behaviors (e.g., Curtis et al. 2014; Tribot et al. 2022; Salazar et al. 2022; Matias et al. 2023; Ison et al. 2024). For example, a recent study by Franquesa-Soler et al. (2020) demonstrated the effectiveness of an arts-based educational program focused on the conservation of black howler monkeys (*Alouatta pigra*). They found that integrating artistic approaches grounded in scientific information led to greater knowl-

edge gains among children and higher overall satisfaction. Similarly, Marchio (2018) explored the role of aquarium keeping as a form of art in communicating science and conservation, whereby maintaining home aquariums helped participants learn about aquatic ecosystems and fostered a personal connection to conservation efforts.

These examples highlight how integrating art and science can engage audiences with underexplored species and ecosystems and foster personal connections to conservation. This approach could also benefit the subterranean world, which remains largely overlooked in public education and conservation efforts. In subterranean science, Danielopol (1998) was among the first to propose that integrating artistic perception with scientific facts could significantly enhance cultural education by emphasizing the unique organisms inhabiting subterranean ecosystems and highlighting their significance in cultural heritage and as public goods with multiple values. While Danielopol's idea compellingly highlights the potential synergy between art and science, it remains abstract, lacking concrete examples or actionable frameworks to fully realize its potential (but see a recent agenda by Gleeson [2024] focused on integrating art in groundwater hydrogeology). We suggest there are many benefits for subterranean scientists engaging with artists and *vice versa* (Fig. 2).

Subterranean ecosystems are invisible to most. As a result, they often end up being marginally represented in conservation policies and actions (e.g., Mammola et al. 2019, 2024; Sánchez-Fernández et al. 2021; Wynne et al. 2021; Fišer et al. 2022; Di Lorenzo et al. 2024). Art can illuminate the hidden subterranean world, reinforcing its ecological importance and interdependence with surface ecosystems (Glanville et al. 2023; Saccò et al. 2024). Artistic projects and exhibitions can draw attention to subterranean ecosystem degradation and galvanize public support for conservation. Furthermore, the emotional impact of art may drive financial backing (e.g., donations) for projects aimed at preserving subterranean biodiversity, especially given the often-limited resources allocated to subterranean conservation. Art can also foster interdisciplinary conservation efforts by encouraging collaboration between scientists, artists, and key stakeholders reliant on subterranean resources, such as farmers and water managers, who often use large quantities of groundwater but lack direct access to or knowledge of these environments.

Art is also central to scientific communication (Fig. 3). Subterranean science is a highly interdisciplinary field at the crossroads of hydrology, biology, geology, anthropology, and many other disciplines, making communication particularly challenging (Martínez and Mammola 2021). Art bridges the gap by transforming complex scientific ideas into accessible or engaging forms. By doing so, these concepts become more relatable and easier to understand, thus supporting education and raising awareness about critical issues surrounding subterranean conservation. Furthermore, art may act as a powerful source of inspiration, sparking curiosity and creativity, which can lead to deeper interest in scientific research and exploration of otherwise unreachable environments. This is particularly important for caves, as these environments are difficult to explore, requiring physical and technical skills, and are therefore only accessible to a small minority of scientists who can experience them directly (MacNeil and Brcic 2017). For example, artists

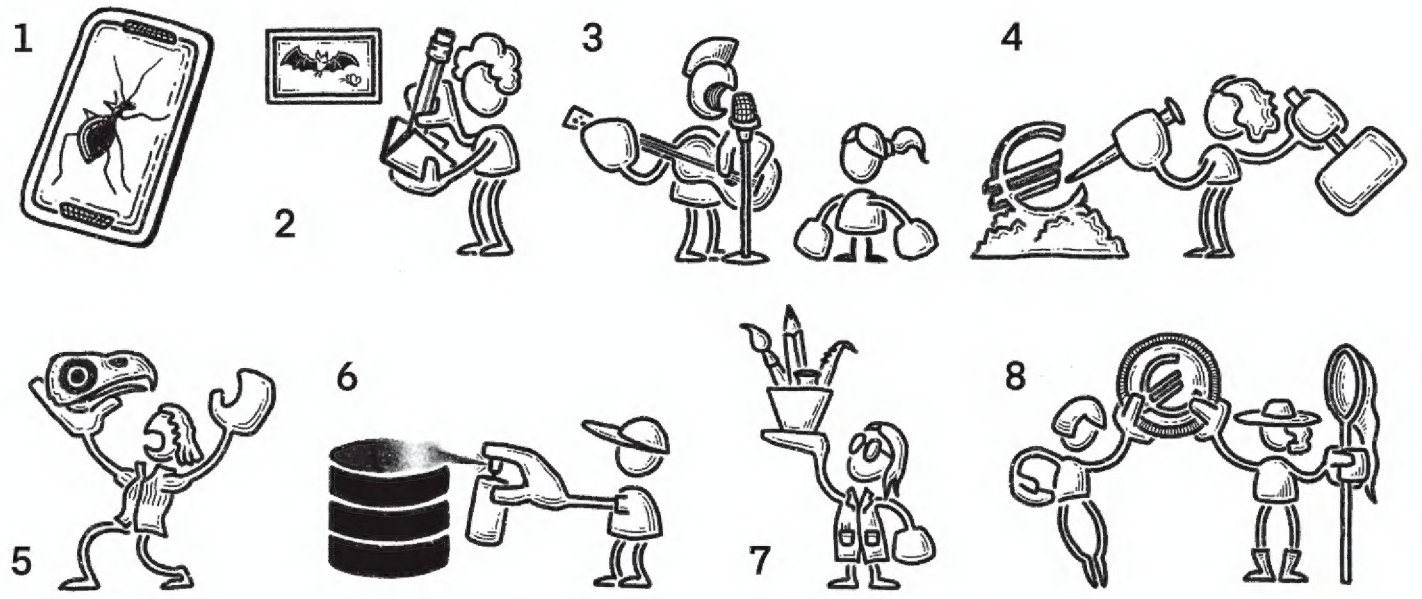


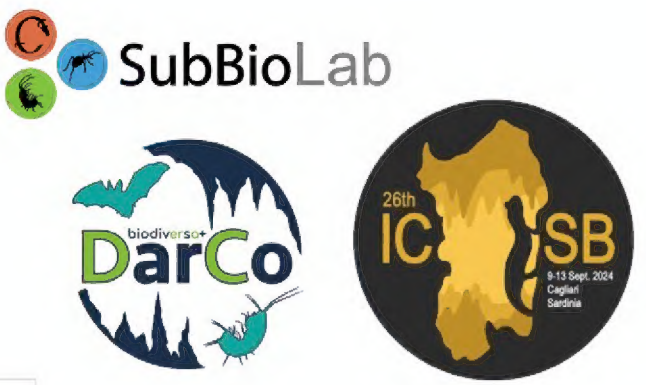

**Figure 2.** Conceptual illustration of synergies between art and subterranean science and conservation. Artistic disciplines can: **1** make subterranean science accessible **2** inspire scientific research **3** enhance education and awareness **4** strengthen conservation projects and attract funding **5** foster interdisciplinary conservation efforts; and **6** contribute to data generation. Conversely, subterranean science projects can: **7** offer material, inspiration, and collaboration opportunities for artists; and **8** support and fund artistic endeavours. Illustrations by Jagoba Malumbres-Olarte.

can play a crucial role during workshops, helping research groups communicate their projects effectively through graphic facilitation in project-specific workshops (Fig. 3e).

Finally, art may serve as a source of data, offering insights through visual documentation and creative interpretations of environmental changes and phenomena (Davis et al. 2025). This concept is well understood by archaeologists, anthropologists, and art historians, who have long used Paleolithic cave art to infer the lifestyles of early humans (Curtis 2007; Whitley 2009). Art can even, in certain circumstances, serve as a valuable source of ecological and conservation information. Figurative art and photography, for instance, have been used to investigate past changes in landscapes, habitats, and ecological conditions (Devrani and Singh 2014; Guagnin et al. 2016; Depauw et al. 2022; Warren et al. 2023). However, no concrete examples of such applications currently exist for subterranean ecosystems, highlighting untapped potential in this area. For example, the painting in Fig. 1d captures a mid-20$^{th}$ century snapshot of the Pugnetto cave community (Sturani 1942). Remarkably, this community continues to thrive today, with all the depicted species still abundant (Mammola et al. 2015, 2017), reflecting the stability and resilience of this unique ecosystem.

## How can we effectively break the cultural divide between subterranean scientists and artists?

Integrating art into subterranean ecosystem research and conservation offers immense potential and benefits, but significant challenges remain. Subterranean scientists and artists often operate in distinct cultural contexts and "speak different languages" which



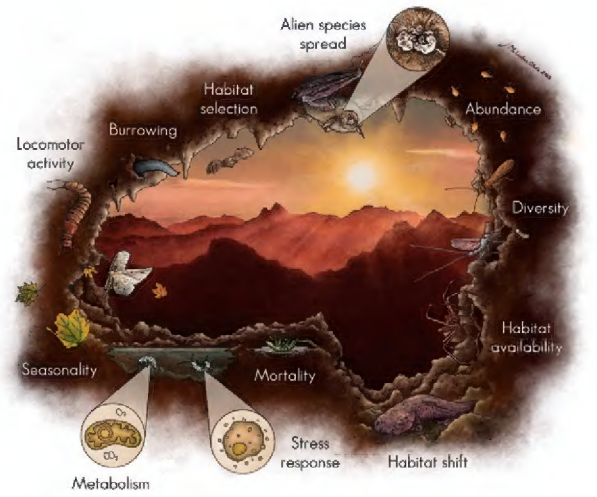


**Figure 3.** Examples of visual art used in scientific contexts to communicate about subterranean ecosystems and their conservation. **a** Photography: Photographs are a powerful tool for showcasing the hidden wonders of the subterranean world, often holding scientific value for cave research (e.g., Kambesis 2007). Pictured: *Troglohyphantes pluto* Di Caporiacco, 1938 (Araneae: Linyphiidae). Credit: Francesco Tomasinelli

can complicate collaborations. Fostering cross-pollination of ideas and exchanges among these professionals does not simply imply avoiding the typical "obscure" speleological jargon to ensure effective communication and idea-sharing (Martínez and Mammola 2021); it demands deliberate and concrete efforts to foster genuine partnerships. In essence, we must explore innovative ways to bring more artists into caves and cavers into studios, bridging these worlds to achieve shared goals.

To effectively integrate art into subterranean conservation, scientists should actively provide artists with the resources and information needed to create compelling and scientifically accurate works. This includes sharing research findings, data, insights, and materials about subterranean ecosystems to enhance the accuracy and depth of artistic interpretations. Recently, the emergence of artificial intelligence (AI) tools (Fig. 1e) has opened new avenues for collaboration between scientists and artists, promising to revolutionize how they operate, create, and interact (Wong 2024). These tools create opportunities to enhance artistic interpretations, but it is important to approach these tools with an awareness of their potential limitations and ethical considerations (Box 1). Given that subterranean ecosystems remain unfamiliar and inaccessible to most, additional efforts to connect artists with these environments are vital. Organizing tours of research sites, such as easily accessible or tourist caves, can provide firsthand inspiration, while inviting artists on research expeditions allows them to gain a deeper understanding of these ecosystems and their significance.

If budget limitations (see next paragraph) or logistical and technical challenges (e.g., caves are often in remote places, artists may lack speleological training) prevent

(http://www.isopoda.net/) **b** logos: Professional logos for labs, projects, and conferences related to subterranean research. Credits: Martin Turjak & SubBioLab (SubBioLab logo), Irene Frigo (DarCo and ICSB logos) **c** infographics: Infographics are powerful tools for teaching best practices in subterranean conservation. Pictured: Best practices for conserving biodiversity in cenotes and their caves ("*Conservación de la biodiversidad de los cenotes y sus cuevas*"). Credits: Nuno S. et al. (www.cenoteando.mx), available on Zenodo (https://zenodo.org/records/10157871; CC BY NC-ND) **d** graphical abstracts: Graphical abstracts provide concise visual summaries of complex scientific studies and help promote papers across different media (Yoon and Chung 2017). Pictured: A graphical abstract by Jagoba Malumbres-Olarte for a meta-analysis of climate change impacts on subterranean ecosystems (Vaccarelli et al. 2023) **e** graphic facilitation involves creating infographics that illustrate and connect the main ideas discussed in conferences, meetings, or workshops. Pictured: Infographic by Jagoba Malumbres-Olarte from a graphic facilitation workshop held by the DarCo research project, focusing on the conservation of subterranean ecosystems in Europe (see "Acknowledgements" for details) **f** conference Illustrations: Illustrations help summarize the main messages of scientific talks and are effective in promoting research, especially on social media. Pictured: Illustration by Jagoba Malumbres-Olarte of a talk by Alice Salussolia at the 26th International Conference on Subterranean Biology (Cagliari, Italy, 9–14 September 2024) titled "Genome skimming and amplicon sequencing: novel DNA-based techniques shed light on the taxonomy and phylogeny of the *N. thuringius* – *N. dolenianesis* species complex (Crustacea, Amphipoda, Niphargidae)". Courtesy of Alice Salussolia **g** comics: Cartoons offer a whimsical yet effective way to deliver the core messages of scientific publications (McDermott et al. 2018) and promote biodiversity conservation (Small 2016). Pictured: A comic by Irene Frigo illustrating the impacts of human activities on subterranean fauna (Mammola et al. 2022a).

bringing artists into field sites, inviting them to scientific conferences and workshops offers an alternative way to share and visualize subterranean science to both academic audiences and the public. Direct invitations are crucial, as such events are often exclusive or poorly advertised beyond the niche community of subterranean biologists and speleologists. For instance, at the 26th International Conference on Subterranean Biology (Cagliari, Italy, 9–14 September 2024), a scientific illustrator was invited to depict a subterranean conservation workshop (Fig. 3e) and several talks (Fig. 3f). These exchanges benefit all parties: artists gain exposure, new ideas, and potential collaborators, while scientists enhance the reach and accessibility of their research. Scientists could organize workshops or lectures tailored for artists, simplifying complex scientific concepts for better understanding. Additionally, collaborative projects with scientists in research institutions provide artists with hands-on experience, fostering a more authentic integration of science in their art (see Clark et al. 2020 for an example).

For such collaborations to succeed, scientists and artists must often address the challenge of securing appropriate budgets to develop joint artistic-scientific work. While institutions and conferences can establish grants, fellowships, and artist residency programs to encourage these collaborations, an often more direct option is for scientists to allocate a portion of their research funding for art-related communication initiatives. These costs will, of course, vary depending on the form of art and level of engagement, with the extent of investment always determined by the total budget and funding scheme. In general, costs for illustrations are minimal compared to other non-primary research expenditures, such as high open-access publication fees (e.g., Van Noorden 2013), and thus often affordable through average research budgets. Other forms of art may be more costly and require more careful planning and valuation. In our experience, allocating about 5% of a project grant to communication expenditures (often art-related) typically allows for fruitful collaborations with artists. For smaller projects (e.g., less than $50,000 USD), such an investment can cover costs to engage artists for logos, illustrations, videos, and other media. For larger grants, a similar percentage investment can potentially cover other expenditures, such as costs for inviting artists to field expeditions, workshops, and conferences, or even stipends for the artists. On a positive note, there is often a return on investment for these expenditures. Including artists in dissemination, communication, and education efforts not only enhances the quality of projects but may increase the likelihood of securing additional funding in the future.

While scientists often act as facilitators or "gatekeepers" of collaborations with artists, bridging the art-science cultural divide may – and should – also be initiated by artists. Artists can undertake projects focused on conservation and related scientific fields, using their own platforms and tapping into funding sources beyond traditional scientific grants. By challenging researchers' communication methods or thinking outside the box, such projects can amplify the impact of their messages and reach broader audiences. Examples include comic books such as "*World without End*" by Blain and Jancovici (2022), which uses artistic tools from literary fiction to attract readers to the subjects of energy and climate, making them accessible and understandable. Indeed, collaboration

with conservationists or experts in the field is also fundamental to avoid scientific inaccuracies or misunderstandings when developing and executing these projects.

Finally, creating exhibitions fully dedicated to subterranean ecosystems – such as the aforementioned "Subterranean" (Amos Rex, Helsinki) and "Subterranean Worlds" (Louvre Lens, Paris) – is likely the most effective way to foster interdisciplinary collaboration and bring these important issues to a wider audience. A recent example, focused on a wide range of ecosystems beyond subterranean ones, is "In praise of diversity" ("*Elogio della diversità*"; Rome, 27 November 2024 – 30 March 2025), an exhibition devoted to the themes of biodiversity and One Health, funded by the National Biodiversity Future Center (NBFC) and curated by the University of La Sapienza. Large exhibitions such as this one have a broad reach and are capable of drawing attention to, and increasing awareness of, the diverse life forms on our planet and our relationship with biodiversity, thereby triggering both individual and collective responsibility. Importantly, the scope of such large-scale exhibitions often exceeds the capacity of a single scientific or artistic grant, necessitating broader involvement from public institutions, art organizations, and private sponsors to co-fund events that highlight the intersection of art and science.

**Box 1.** The role of AI in art and science collaboration.

At the time of writing, recent advancements in AI have opened new opportunities for collaboration between artists and scientists. This is an emerging and rapidly evolving field, with new tools constantly being developed, making it difficult to chart future trajectories. Many text-to-image AI tools, such as DALL-E and Midjourney, can already assist in creating complex, accurate, and engaging visualizations and animations of scientific data (Wong 2024). For instance, AI algorithms can process large datasets, simulate environmental changes, and generate dynamic visualizations, such as 3-dimensional models of subterranean ecosystems or time-lapse animations of ecological and geological processes therein. These capabilities provide unprecedented – and often costless – opportunities to bridge the gap between scientific rigor and artistic expression, which may be particularly useful for difficult-to-experience ecosystems such as caves.

However, these advancements come with important caveats and limitations. First, human supervision and validation (preferably by a team of artists and scientists) is crucial to avoid oversimplification or distortion of scientific concepts (see, e.g., Guo et al. 2024 for a recent example of a retracted article due to the misuse of AI-generated figures). Second, ethical concerns arise regarding the use of AI in art, particularly around intellectual property and authorship. When AI tools generate artwork, questions about ownership and the recognition of human creators must be addressed, emphasizing the importance of being transparent about the role of AI during the creative process. Third, the rise of AI may impact professional artists. While AI can support artists by automating repetitive tasks and enabling new creative possibilities, it may also pose a threat to traditional artistic roles, particularly in commercial fields where cost-efficiency often takes precedence. It is thus very important to positioning AI as a complementary tool rather than a replacement, ensuring it enhances human artistic contributions rather than diminishes them.

## How can we test the effectiveness of art in enhancing communication about subterranean ecosystems and their conservation?

There is growing evidence that art is a powerful ally in scientific communication and that arts-based conservation education is central to successful conservation programs (Clark et al. 2020). Matias et al. (2023) conducted a meta-analysis showing that art contributes to coastal and marine conservation by engaging people, promoting dialogue, and increasing knowledge. Importantly, 19 out of 79 articles in their dataset assessed quantitatively the impact of artistic activities on audiences and conservation outcomes. One example is the Aula Verde Project, where artists, scientists, and environmental activists worked together to reconnect citizens with nature in urban areas. This effort resulted in the creation of a Land Art installation in Rome that serves both as a nature-based solution and a space for social interaction. The project evaluated the ecosystem services provided by this urban forest, demonstrating its potential over the next 50 years to store carbon (48 tons), remove air pollutants (11,000 grams), and prevent surface runoff (48 $m^3$ per year) (Conte et al. 2024).

Yet, any reader who has made it this far may have noticed that this perspective focused on subterranean ecosystems does not present any quantitative data to complement the discussion. This is due to the lack of quantitative testing on how effective the synergies between subterranean science and art truly are. More broadly, there has been limited testing of the effectiveness of conservation actions in subterranean ecosystems (Mammola et al. 2022b; Meierhofer et al. 2024). A recent systematic review found that only 31% of recommended conservation actions for subterranean ecosystems have been rigorously tested for effectiveness (Mammola et al. 2022b). Similarly, Meierhofer et al. (2024) reported that just 34% of specific conservation actions for subterranean-dwelling bats have undergone testing. This lack of rigorous evaluation is particularly striking in the areas of education and communication, where the effectiveness of such activities has never been assessed (Mammola et al. 2022b; Meierhofer et al. 2024). This gap may discourage scientists from collaborating with artists, though examples of such partnerships in conservation science remain common despite the overall scarcity of evidence (see examples in Fig. 3). There are numerous ways to address this knowledge gap.

### Scientometric approaches

A straightforward way to test the impact of art on science communication is through state-of-the-art scientometric approaches. Scientometrics, or the "science of science," uses quantitative methods to analyze the performance and impact of scientific research, including researchers, journals, institutions, or fields of science (Fortunato et al. 2018). In our case, by examining a geographically and/or temporally coherent sample of literature focused on subterranean ecosystems – e.g., a sample of papers from journals like *Subterranean Biology* or *International Journal of Speleology* – researchers could compare the performance of papers containing artistic elements (e.g., illustrations, diagrams, or visual representations) to those without. Metrics such as citations, Altmetric scores,

and social media engagement could be used to evaluate the relative impact of artistic elements on publication performance (Kwok 2013; Bornmann 2014; Tahamtan et al. 2019). To ensure validity, the analyses would need to account for confounding factors, including both scientific and non-scientific characteristics of the papers (Tahamtan et al. 2019; Mammola et al. 2022c). Although primarily applicable within academia, this method would ultimately provide valuable quantitative evidence of the role art plays in enhancing the visibility and accessibility of scientific works. Given that publication metrics are a primary driver of career progression in academia, quantitative evidence of art's impact on the success of scientific outputs could serve as a strong incentive for researchers. In the long term, similar evidence might encourage more researchers to seek the help of and actively involve artists as collaborators, fostering a positive transformation in the relationship between these two fields.

## Fundraising campaigns

Funding availability is a key limiting factor for conservation efforts (Waldron et al. 2017). Therefore, measuring conservation success through economic proxies offers a practical approach. For example, Kubo et al. (2022) demonstrated that advertisement design significantly impacts donor engagement in digital conservation fundraising. Their study tested the effectiveness of three types of advertisements: simple (control), seed money (indicating 55% progress of the fundraising target), and ecological (highlighting the threatened status of the target species). Drawing inspiration from this, similar fundraising campaigns could be designed for subterranean ecosystems to assess the impact of art. For instance, fundraising campaigns for cave conservation could be divided into those emphasizing artistic elements and control campaigns without them. The effectiveness of these campaigns could be evaluated in two ways: first, by comparing financial outcomes – do advertisements featuring artistic elements attract more donors? Second, by surveying donors and visitors to understand their motivations – does the presence of art influence their willingness to contribute or engage? These insights could illuminate how art enhances conservation efforts and public support, again representing a strong incentive for both artists and scientists to seek more collaborations and apply for joint grants and projects.

## Social sciences

Beyond quantitative approaches, social science methods can provide deeper insights into how art shapes public perceptions of subterranean ecosystems and their conservation. Qualitative techniques such as interviews, focus groups, and online or in-person surveys in tourist caves can explore the emotional and cognitive effects of art (Dans and González 2019). For example, researchers could examine whether artistic representations evoke emotional responses – such as awe, curiosity, or empathy – that increase awareness of conservation issues. They could also assess whether art enhances memory retention of key ecological concepts or conservation messages. An-

other promising source of information is online data, particularly social media, which represents an emerging field of conservation culturomics (Ladle et al. 2016; Correia et al. 2021). Through the quantitative analysis of online digital data – such as social media, news platforms, webpage visitation rates, and internet search activity – culturomics can provide valuable insights into public values, awareness, interests, and attitudes related to art-science projects and initiatives, as well as the effectiveness of art-based public communication activities. For instance, it can be used to evaluate the effectiveness of social media campaigns promoting subterranean conservation issues by comparing public engagement with posts that feature artwork versus those that do not, or by conducting sentiment and topic analyses of social media content related to art-science activities. Simultaneously, public engagement can be evaluated beyond the digital realm by tracking participation in art exhibitions or theater performances focused on subterranean ecosystems. Understanding these emotional and cognitive dimensions offers valuable insight into how art fosters public engagement and support for subterranean conservation efforts.

## A short final note on the potential environmental impacts of subterranean art

Subterranean ecosystems are particularly vulnerable to human disturbance due to their isolation and often pristine conditions. Introducing art, artists, and visitors into caves and subterranean sites can have localized impacts. For instance, organizing concerts or theater performances in tourist caves can lead to a large number of visitors temporarily occupying the subterranean environment (Fig. 1g). This activity can alter local thermal conditions, disturb native fauna, and introduce waste or external organic matter, including non-native fungi and bacteria (Piano et al. 2024). In extreme cases, tourists may even damage cave structures, such as speleothems, or harm cave art. An example is illustrated by the closure of caves such as Chauvet, Altamira, and Lascaux, whose delicate prehistoric wall art experienced microbial and fungal outbreaks due to mismanaged tourism and the improper removal of invasive microbial biofilms (Bastian et al. 2009). Furthermore, excessive or ill-suited artificial lighting can also promote the growth of photosynthetic organisms (often referred to as lampenflora) on cave walls (Baquedano Estévez et al. 2019; Piano et al. 2024). While these impacts are notable, they are likely minor compared to the long-term benefits of raising public awareness about subterranean ecosystems, which can have lasting effects on people's willingness to support conservation (Mammola et al. 2022). However, precautionary measures should always be taken to minimize these impacts (see, e.g., Chiarini et al. 2022; Piano et al. 2024 for a review of management options).

These measures include temporarily limiting the number of visitors allowed to access the subterranean artwork or exhibition to minimize several of the impacts mentioned above, adopting shoe and clothing cleaning practices at the entrance of the cave to prevent the introduction of alien organisms, using lighting systems that discour-

age the growth of lampenflora, and selecting less susceptible areas within caves for the placement of artworks. Furthermore, scientists can assist artists in creating more sustainable artwork by recommending eco-friendly materials and considering the geological and environmental context of the specific cave targeted for the art exhibition. In cases where caves are closed to the public for conservation purposes, cave replicas – full-scale reproductions of cave interiors and their art – offer an effective strategy to mitigate over-tourism. Notable examples include Altamira in Spain and Lascaux II, Lascaux IV, and Chauvet II in France, where teams of artists and scientists have recreated cave art using diverse approaches, including immersive technologies such as augmented reality and 3D projections. These replicas enable visitors to appreciate cave art while safeguarding the original sites' cultural artifacts and delicate subterranean ecosystems. Meanwhile, researchers continue to conduct scientific investigations in the natural caves, providing valuable insights to inform ongoing conservation efforts (Bastian et al. 2010; Geneste et al. 2014; Hughes et al. 2021).

When considering all these precautionary measures, it is important to remember that they are context-specific and must be tailored not only to the unique characteristics of the cave or subterranean site in question but also to the nature of the artwork itself.

## Conclusions

Subterranean ecosystems have inspired artistic expression for millennia, from Paleolithic cave paintings to contemporary abstract performances. While there is no quantitative evidence yet that art directly advances subterranean conservation, our dual experiences as scientists who appreciate art – and as artists who appreciate science – suggest that deeper connections between these realms can have profound and long-lasting impacts on both scientific communication and conservation. Art has the unique ability to make complex scientific concepts more accessible, foster interdisciplinary collaboration, attract critical conservation funding, and even provide unexpected sources of data. By collaborating with artists, subterranean scientists can create more impactful visuals for research papers and presentations, engage the public through captivating storytelling, and inspire fresh insights that may drive new research directions. To maximize these benefits, scientists should nurture partnerships with artists. Allocating small portions of research budgets for art-related initiatives, inviting artists to conferences and workshops, and including them in cave expeditions are all meaningful steps toward fostering meaningful collaboration. Artists, in turn, can initiate collaborations by developing independent conservation projects, using their own platforms to advocate for subterranean conservation, and promoting innovative artistic approaches that challenge researchers to rethink scientific communication and engagement. Ultimately, these partnerships can spark creativity, generate new ideas, and ensure the unseen world beneath our feet garners the attention it deserves – for the advancement of both science and conservation.

## Conflicts of interest

Stefano Mammola is a Subject Editor of *Subterranean Biology* but took no part in peer-review and editorial decisions for this manuscript.

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